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## Monitoring Sources of Nuclear Radiation in Space 1985-1987 Observations

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<p>The gamma-ray spectrometer (GRS) on NASA's Solar Maximum Mission satellite (SMM) has been monitoring Soviet nuclear reactors in space since 1980 when it detected radiation from COSMOS 1176. Direct observations of gamma radiation were made within about 500 km when the RORSATS were not occulted by a significant amount of material in SMM. Indirect observations were also made up to distances in excess of a few thousand kilometers. These observations were made when positrons and electrons produced in the outer layers of the reactor-powered spacecraft reached SMM after being stored in the Earth's magnetic field.</p> <p>In this report we provide details of SMM's observations of the four RORSATS launched in 1985 and 1986, and compare these with</p>					
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## 19. ABSTRACTS (Continued)

measurements made of the seven RORSATS detected from 1980 to 1984. The average intensities from all the eleven reactor-powered satellites are consistent with each other, after correcting for distance of separation. The observed increase in the rate of distant detections of positrons from 1980 to 1984 is due to the decreasing atmospheric density above a few hundred km in the transition from maximum to minimum solar activity. The rate did not change significantly between 1984 and 1986.

A composite gamma-ray spectrum created from a summation of close-approach sightings of the eleven RORSATS is presented. It is not possible to obtain a unique interpretation of this spectrum. One relatively simple model of the gamma-ray spectrum emitted from the RORSATS which fits the data reasonably well includes the following components: a fission continuum from  $^{235}\text{U}$  and neutron capture lines from molybdenum embedded within tens of g/cm<sup>2</sup> of material; two unresolved lines near 500 keV attributed to a line at 511 keV from positron-annihilation and to a line near 477 keV from boron. Other neutron capture lines may contribute to the observed spectrum.

On February 1, 1987 the Soviet Union launched a new satellite, COSMOS 1818, into a higher orbit (790 km) than previously launched RORSATS. Within 8 hours of its launch the SMM spectrometer detected both a 511 keV event from positrons stored in the earth's magnetic field and direct gamma radiation at a distance of about 450 km. These measurements confirm that the power source of the satellite is a nuclear reactor. The rate of distant detections of positrons and electrons is a factor of ten higher than that observed from any previous reactor powered spacecraft. This increase is primarily attributed to the much longer lifetime of these particles due to the significantly lower atmospheric density at the orbital altitude of COSMOS 1818.

The integrated gamma-ray intensity is over a factor of two higher than previous RORSATS. Most of this increase is observed at energies below about 5 MeV. The measured flux above 6 MeV is consistent with that measured from the earlier RORSATS. This suggests that the higher gamma-ray emission may be due to differences in the amount of material between SMM and the reactors. The overall spectral features observed from COSMOS 1818 are similar to those observed from the earlier RORSATS, suggesting that the basic reactor design is not significantly different. Ten independent measurements of the gamma-ray emission were made over the 5 month lifetime of COSMOS 1818. With the exception of a single observation occurring late in the mission, the data are consistent with a gradual increase of up to about 40% in gamma-ray emission from February to July.

A second high-altitude reactor powered spacecraft, COSMOS 1867, was launched in July 1987. Detailed analysis of data pertaining to this system has not been completed; however, its emissions appear to be similar to that observed from COSMOS 1818.

The increased emission and orbital lifetimes of positrons and electrons from systems like COSMOS 1818 and 1867 create a significant background problem for high sensitivity gamma-ray instruments in near-earth orbit.

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# MONITORING SOURCES OF NUCLEAR RADIATION IN SPACE

## 1985-1987 OBSERVATIONS

### I. INTRODUCTION

The gamma-ray spectrometer on NASA's Solar Maximum Mission satellite (SMM) first detected radiation from a nuclear reactor in space in 1980, following the launch of COSMOS 1176. COSMOS 1176 was one of a series of Soviet satellites with the acronym RORSAT, which stands for Radar Ocean Reconnaissance SATellite. Details of the history of these measurements can be found in an earlier report (Share, Kurfess, Marlow, et al. 1989). Direct observations of gamma radiation were made within about 500 km when the view of the RORSAT was not blocked by a significant amount of material in SMM. Indirect observations were also made at distances up to in excess of a few thousand kilometers when positrons and electrons produced in the outer layers of the RORSAT were detected by the SMM spectrometer after being stored in the geomagnetic field. The positrons were unambiguously identified by the 0.511 MeV gamma-ray line produced when they annihilated in local material near the spectrometer.

A previous report (Share, Kurfess, and Messina 1989) summarized measurements of nuclear radiation emitted from seven RORSATS launched by the Soviet Union from 1980 to 1984. The average integral gamma-ray intensities from the seven satellites, after correcting for distance of separation, were consistent with each other to within 30%. In contrast, the rate of distant detections of positrons increased with time over the four-year period. The rate of detections was about 0.2/day in 1980 and 0.7/day in 1984. This increasing rate was explained as being due to the decreasing atmospheric density above a few hundred km due to the reduction in solar activity. A composite gamma-ray spectrum from a summation of close-approach sightings of the seven RORSATS was presented. It was not possible to obtain a unique interpretation of this spectrum. A relatively simple model of the gamma-ray spectrum emitted from the RORSATS which provided a fair fit to the data included the following components: 1. a fission continuum from  $^{235}\text{U}$ , 2. neutron capture lines from molybdenum embedded within tens of g/cm<sup>2</sup> of material, and 3. two unresolved lines near 500 keV from positron-annihilation (511 keV) and boron (477 keV).

In Section II of this report we summarize observations of nuclear radiation from the four RORSATS launched in 1985 and 1986: COSMOS 1670, 1677, 1736, and 1771. These measurements are compared with observations made from 1980 to 1984. The rate of detections of 511 keV events due to positrons stored in the earth's magnetic field appears to be consistent with what was observed in 1984. The relative intensities and spectra of gamma radiation emitted by these four reactor-powered spacecraft are also consistent with SMM measurements of earlier RORSATS.

On February 1, 1987 the Soviet Union launched a new type of spacecraft, COSMOS 1818, into an orbit with the same inclination as the earlier RORSATS, but at a much higher altitude (790 km versus 260 km). Nuclear radiation from this spacecraft was detected by SMM within hours of its launch, confirming that it was powered by a nuclear reactor. The SMM observations of radiation from COSMOS 1818 are summarized in Section III. The rates of detections of positrons and electrons stored in the Earth's magnetic field after emission from the spacecraft are over an order of magnitude higher than observed from the lower altitude RORSATS. The integrated intensity of gamma-radiation from COSMOS 1818 is more than a factor of two higher than any of the earlier reactor powered spacecraft and its spectrum is considerably softer.

We discuss the implications of the latest observations in Section IV.

## II. 1985-1986 OBSERVATIONS

Nuclear radiations from four RORSATS in operation from 1985 through 1986 were detected by the SMM spectrometer. These satellites are identified as COSMOS 1670, 1677, 1736, and 1771.

### A. DISTANT DETECTIONS

The SMM gamma-ray spectrometer detected electrons and positrons stored in the Earth's magnetic field following their emission from outer materials of the four RORSATS launched during this time period. The rate at which these detections were made was about the same as the rate observed from RORSATS observed in 1984. These results are summarized in Figure 1, which shows the rate at which bursts of 511 keV line gamma-rays (a monitor of positrons encountered by SMM) were detected from individual satellites as a function of time. The rates have been averaged over sightings made each year since 1980. As we noted in an earlier report (Share, Kurfess, and Messina 1986), this rate increased up until 1984.

This rise was attributed to the increased lifetime of the positrons due to the reduced density of the upper atmosphere with the approach of Solar minimum. The rates in 1985 and 1986 are slightly below, but still consistent with those in 1984. We expect the rate of events detected from similar reactor systems, orbiting at the same 260 km altitude, to decrease in the ensuing years as the new activity cycle of the sun approaches.

## B. DIRECT OBSERVATIONS

Due to the continuing excellent stability of the spectrometer, we are able to compare the relative gamma-ray emissivities of the eleven RORSATS in operation from 1980 through the end of 1986. We once again utilized the integral rate of gamma-rays detected in the energy range from 0.8 to 8.0 MeV during close-approach sightings ( $< 400$  km) when the RORSATS were within about  $70^\circ$  of the spectrometer's axis of detection. The rates were integrated over the 49 s integration period when the RORSATS were closest to SMM. The background was estimated from rates observed within a few minutes of the detection. The difference between the on-source and background rates were then normalized to detection at an average separation of 300 km, under the assumption that the emission is isotropic. We have only included sightings for which we have confidence that the background is well determined.

Our measurements of the average integral 0.8 - 8.0 MeV gamma-ray intensities from each of the eleven RORSATS observed by SMM prior to 1987 are plotted in Figure 2. The errors shown include the statistical uncertainties in the on-source and background counting rates, and the uncertainty in the mean separation of the satellites. The average rates range from about 250 cts/16 s to about 365 cts/16 s (normalized to a separation of 300 km). Using a Chi-square analysis we find the rates plotted in Fig. 2 agree at a confidence level of 5% with the premise that there is no significant difference in gamma-ray intensity. We attribute any differences in intensity to variations in shielding of the reactor and to uncertainties in the average distance of separation.

We have studied the emitted gamma-ray spectra from RORSATS observed by the SMM spectrometer from 1980 to the end of 1986. These spectra were obtained from the close-approach sightings described above. Inspection of these spectra indicates that the gross features of the gamma-ray emissions from the individual spacecraft do not differ significantly. An integrated count-rate spectrum from close-approach sightings of the eleven RORSATS is shown in Figure 3. This spectrum was accumulated over 2519 s when SMM was within about 400 km of the COSMOS satellites. For purposes of presentation, the original 476 channel spectrum has been compressed so that the plotted rates in each channel are statistically significant.

The general features of the spectrum shown in Figure 3 are similar to what we described in an earlier report (Share, Kurfess, and Messina 1989). The spectrum is hard with emission extending up to about 7 MeV, above which energy the rate falls rapidly. Aside from this high-energy cutoff, the most striking feature occurs near 500 keV. These two significant spectral features provide the most unambiguous information concerning the makeup of the reactor. There is also considerable information both in the shape of the continuum and in apparent weaker features, but the interpretation is not unique. This is true because these shapes can arise from a combination of a variety of sources embedded in an undetermined amount of material. In our earlier report (Share, Kurfess, and Messina 1989) we describe a simple attempt to model the features observed in the spectrum.

This model consists of a source emitting a composite spectrum of radiation from fission of  $^{235}\text{U}$  and neutron capture in Mo, embedded under about 50 g/cm<sup>2</sup> of aluminum, and a blend of the 477.6 keV line from  $^7\text{Li}$  produced by the (n, alpha) reaction on  $^{10}\text{B}$  and the 511 keV annihilation line.

### III. OBSERVATIONS OF COSMOS 1818

COSMOS 1818 was launched at 23:30 UT on 1 February 1987. The SMM spectrometer observed a 511 keV transient event about 5 hours later. The event was similar to those observed when a RORSAT was in operation and was consistent with the detection of magnetically trapped positrons from COSMOS 1818. About 20 more 511 kev events were observed over the next week. At 08:34 UT on 2 February this new spacecraft passed within 438 km of SMM and was also within the field of view of the gamma-ray spectrometer. The spectrometer recorded a striking increase in the local gamma-ray intensity during that time period. The measured spectrum of the radiation was similar to that observed from RORSATS confirming that the power source on COSMOS 1818 was a nuclear reactor.

#### A. DISTANT DETECTIONS

The rate of events associated with trapped electrons and positrons for COSMOS 1818 was ten times that for previously observed RORSATS. This is illustrated in Fig. 4, which shows the time history of 511 keV annihilation line events (positrons) recorded from February to the beginning of June. The apparent periodic variation of the events is most probably due to variations in detectability caused by the different orbital precession rates of SMM and COSMOS 1818. We plot similar time histories for electron events and the total charged-particle events, in Figures 5 and 6.

Inspection of Figure 6 indicates that the rate at which the charged-particle events are detected varies in a regular fashion. There are no significant deviations in the daily rate as compared with the long-term trend (the rates on days 78, 113, and 155 appear to be lower because the detector operated for only part of the day). This suggests that the day-to-day power level of the reactor on COSMOS 1818 did not vary by more than about 50% during the ~140 day period of observation.

These transient particle events exhibit a large variety of durations and shapes. They vary from seconds to tens of minutes in duration and frequently occur more than once per orbit. Two examples of these events are shown in Figures 7 and 8. A detailed explanation of how electrons and positrons emitted by satellite-borne reactors can reach the SMM spectrometer has been given by Hones and Higbie (1989). Their analysis utilizes the McIlwain 'L' parameter, which is defined as the distance (in Earth radii) where a magnetic field line crosses the

geomagnetic equator. Particles trapped along the earth's magnetic field drift in longitude (eastward for electrons; westward for positrons) so as to remain at the same 'L' value. The basic problem is to determine whether SMM has reached a given 'L' value at the proper time such that a cloud of electrons/positrons would be detected. Detailed explanations of the event rates shown in Figures 7 and 8 are given below.

The charged particle rate plotted in Figure 7b exhibits an increase near the 5 minute mark. At this time SMM was at an 'L' value of about 1.12 and began detecting the cloud of electrons emitted from COSMOS 1818 about a minute earlier, when it was at the same 'L' value. The electron rate observed over the next four minutes remained relatively constant as SMM tracked the same 'L' values reached by COSMOS a few minutes earlier. A sharp spike in the rate occurred at about nine minutes as SMM reached an 'L' value of 1.08. This was the minimum 'L' value attained by COSMOS and it deposited radiation onto this shell for about two minutes. This explains the increase in the intensity of electrons encountered by SMM. The abrupt decrease in the rate occurred at the same time that SMM moved to lower 'L' values than the minimum reached by COSMOS; no electrons emitted by COSMOS are expected on these magnetic field lines. A sharp rise in rate, at reduced amplitude, is observed after about 17 minutes as SMM again reached the minimum 'L' shell onto which particles from COSMOS were deposited.

The time history of annihilation line detections shown in Figure 8 can be explained in a similar manner. Prior to about the 12 minute mark, SMM was located at 'L' values lower than any reached by COSMOS. The spike in the rate of 511 keV line detections occurred at the 12 minute mark, just as SMM was at the same 'L' value as COSMOS. This was also at the minimum 'L' value for COSMOS, which allowed more particles to be emitted along magnetic fields lines in this region. The rate decreased as SMM moved to higher 'L' values than COSMOS and away from the clouds of positrons deposited about 10 minutes earlier by COSMOS. The peaks at about 27 and 60 minutes once again occurred when both SMM and COSMOS were lined up on the same magnetic field. In the latter case the rate peaked about a minute later than the time when the 'L' values were the same. This happened because COSMOS and SMM were crossing each other in the opposite direction in 'L'; therefore SMM could only detect positrons after their 'L' trajectories crossed, at such times when positrons deposited about a few minutes earlier could reach it. The peaks at 46 and 52 minutes are due to positrons deposited by COSMOS over 35 minutes earlier when it reached its minimum 'L' value of ~1.1. The sharp fall of the peak at 47 minutes and the sharp rise of the peak at about 52 minutes mirror what was observed in Figure 7b and have the same explanation; between those times SMM reached 'L' values below that reached by COSMOS and therefore no positrons could be detected.

## B. DIRECT OBSERVATIONS

Several measurements have been made of the gamma-radiation emitted by COSMOS 1818. These observations were made over an ~49 s interval when COSMOS was both within ~400 km of SMM and within 70° of the spectrometer's axis of detection. This enabled us to compare its gamma-ray emissivity and spectrum with those obtained for the eleven RORSATS observed from 1980 to 1986.

Shown in Figure 9 is a comparison of the average rates, normalized to a satellite separation of 300 km, observed by SMM in the 0.35 to 0.8 MeV and 0.8 to 8.0 MeV bands from the twelve reactor-powered spacecraft. The fluxes of gamma-radiation from COSMOS 1818 are significantly higher than those observed from the earlier RORSATS. The normalized rate from COSMOS 1818 in the 0.35 to 0.8 MeV band is  $845 \pm 50$  cts/s compared with  $335 \pm 15$  cts/s for the average of the earlier RORSATS. In the 0.8 to 8.0 MeV range a rate of  $599 \pm 36$  cts/s was observed from COSMOS 1818, while  $305 \pm 12$  cts/s was the average observed for the RORSATS. The rate increased by a larger factor, 2.5, in the 0.35 to 0.8 MeV band than the factor, 2.0, observed in the 0.8 to 8.0 MeV band. This suggests that the gamma-ray spectrum from COSMOS 1818 was softer.

Plotted in Figure 10 is the count rate spectrum accumulated during 522 s when COSMOS 1818 was both within about 500 km of SMM and within 70° of the gamma-ray spectrometer's detection axis. The overall appearance of the spectrum is similar to that displayed in Figure 3 which displays the accumulated data from eleven RORSATS. The COSMOS 1818 spectrum exhibits both the sharp decrease above ~7 MeV and the broad feature near 511 keV that are characteristic of the spectra observed from these earlier reactor-powered spacecraft. For comparison we have plotted a smoothed representation (dashed curve) of the spectrum shown in Figure 3. Both spectra have been normalized to the same average distance of separation. It is clear from this comparison that the spectrum from COSMOS 1818 is enhanced at energies below ~5 MeV; while it is not significantly more intense above ~6 MeV. We obtain a value of  $1.17 \pm 0.15$  for the ratio of the fluxes observed above 6 MeV from COSMOS 1818 relative to the earlier RORSATS.

We have also used these direct sightings of COSMOS 1818 in order to search for any significant variability in its gamma-ray emission during its operational lifetime. Integrated intensities for the ten direct sightings of COSMOS 1818 are displayed in Figure 11 in two energy bands (0.35 - 0.8 MeV and 0.8 - 8.0 MeV); all the rates have been normalized to a distance of observation of 300 km. The data in both energy ranges were fit by linear functions. Both fits suggest that the integrated gamma-ray intensity increased with time; however, the intensity on day 148 was considerably below the trend exhibited by the other data points. If we assume that the observation on day 148 was spurious, then the data in both energy bands are consistent with an increase in gamma-ray flux of about 40% from February to July.

#### IV. DISCUSSION

We have shown that the nuclear radiation emitted from the four RORSATS detected by SMM in 1985 and 1986 is similar to that observed from RORSATS observed from 1980 to 1984. The rates of detection of secondary positrons and electrons from the shell of the spacecraft are consistent with the earlier observations and the magnetic field storage model. The relative intensities observed from the eleven satellites are consistent with each other to within about 30%.

The SMM observations of COSMOS 1818 show a marked difference from those of the earlier RORSATS. Perhaps the most striking difference is the frequency of detection of magnetically trapped positrons and electrons emitted from the spacecraft. This rate is over a factor of ten higher than for any previously detected reactor-powered spacecraft. This increase can, in large part, be attributed to the higher altitude of COSMOS 1818. This is true because of the much lower atmospheric density at that altitude. Positrons and electrons emitted at 790 km can remain trapped in the earth's magnetic field without being dumped into the atmosphere for periods in excess of an hour. Typical lifetimes for the particles emitted from the RORSATS at 240 km were at most on the order of 5 to 10 minutes. This increased lifetime increases the probability that SMM will traverse a field line on which the particles are stored. The increase is proportional to the lifetime, so an increase by about an order of magnitude is consistent with the observations. A possible additional explanation for the increase in the rate of trapped particle events is that SMM and COSMOS 1818 are magnetically coupled more frequently due the higher altitude of 1818.

The other significant difference is the relative softness of the spectrum emitted by COSMOS 1818 relative to previous RORSATS. The fact that the emissivity from COSMOS 1818 at energies above about 6 MeV is not significantly different than that observed from the RORSATS suggests that the amount of shielding between SMM and the reactor plays a significant role in creating this disparity. Aside from this difference in the shape of the spectral continuum at lower energies, the spectrum from COSMOS 1818 exhibits many of the features exhibited by previously launched RORSATS. This suggests that the fundamental design of the reactor is not significantly different from earlier models.

There is evidence in the SMM data for an increase in the overall gamma-ray emissivity of COSMOS 1818 over its 5 month lifetime. This increase could be as much as about 40%.

Four more reactor-powered satellites were launched by the Soviet Union after COSMOS 1818. One of these, COSMOS 1867, is at the same operational altitude as COSMOS 1818. It was launched in July 1987 and was still in operation as of the beginning of June 1988. Our preliminary studies indicate that its gamma- and beta-ray emissions are similar to those from COSMOS 1818.

The launch of these higher-altitude reactor-powered spacecraft has seriously affected the ability of sensitive gamma-ray spectrometers, such as SMM, to conduct celestial and solar observations. This is primarily a result of the increased background in both 511 keV line and continuum emissions due to the increased emissions of electrons and positrons, and their much longer lifetimes. If the number and operating power of space reactors increases, the ability to conduct X- and gamma-ray observations from near-earth platforms will be in severely restricted.

## V. ACKNOWLEDGMENTS

We wish to acknowledge our colleagues Prof. E.L. Chupp and Dr. D.J. Forrest of the University of New Hampshire, under whose direction the gamma-ray spectrometer was built. Their assistance in our understanding of the instrument's performance has been essential. We also wish to thank the personnel of NAVSPASUR for providing ephemeris information vital to the analysis of the data.

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Share, G.H., Kurfess, J.D., Messina, D.C. 1989, NRL Memorandum Report 6467.

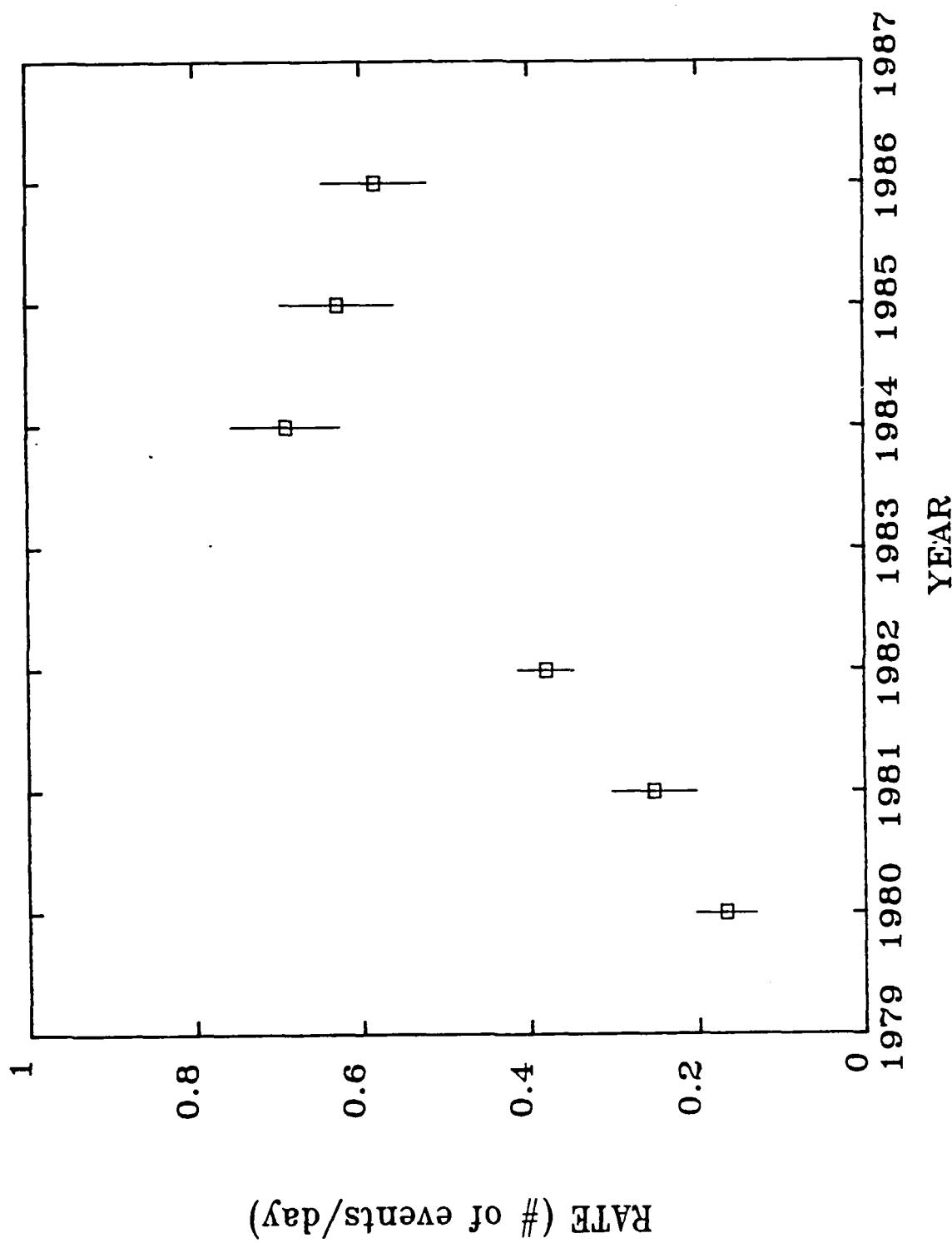


Fig. 1 - Rate of detections of bursts of annihilation radiation found in a computer search of the SMM data. Rates plotted are number of annihilation events divided by days of RORSAT operation in a given year.

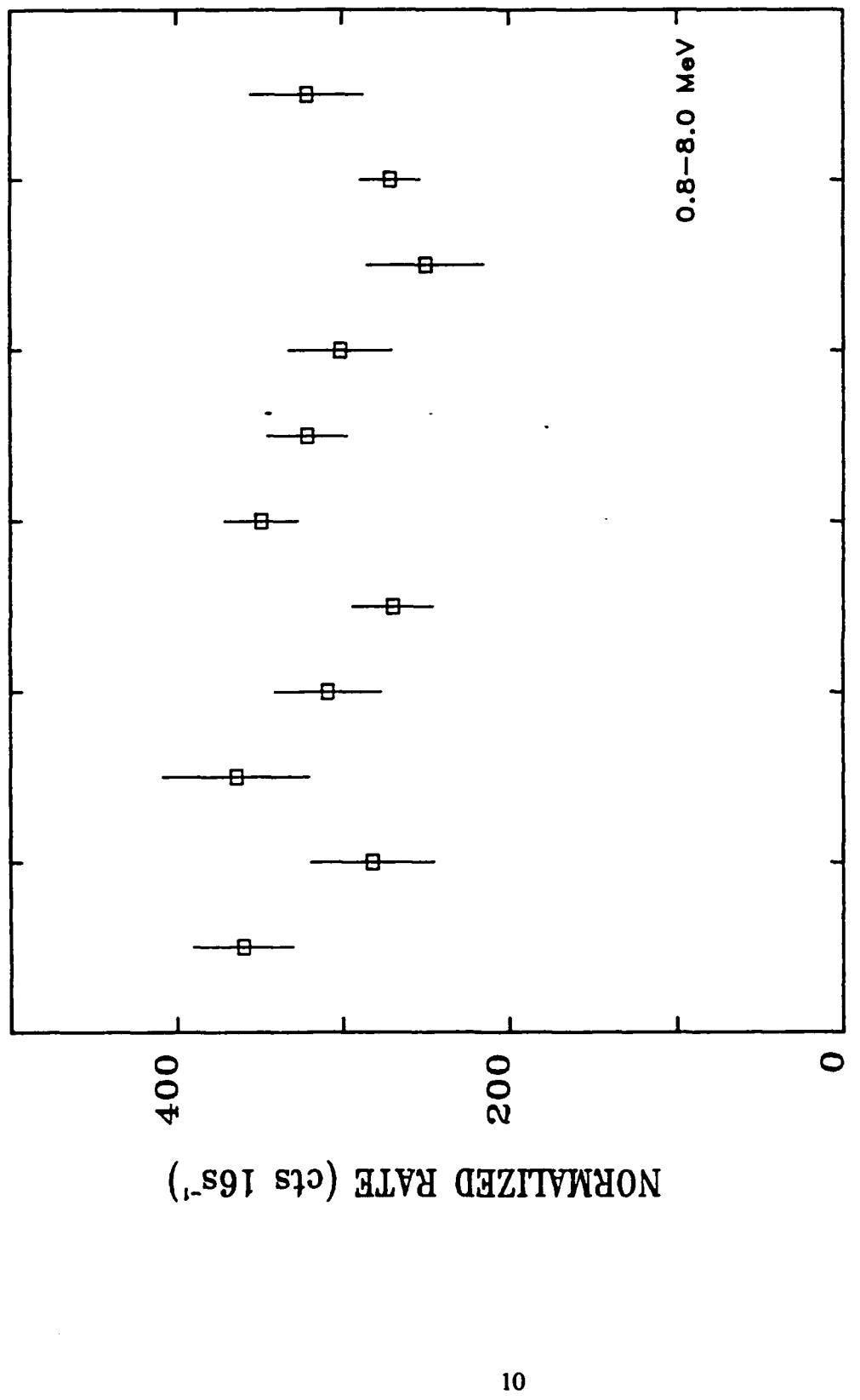


Fig. 2 - Average 0.8 to 8.0 Mev counting rates in the SMM spectrometer, normalized to 300 km, during close-approach sightings of the eleven RORSATS observed prior to 1987. The COSMOS identification numbers from left to right are: 1176, 1249, 1365, 1372, 1402, 1579, 1607, 1670, 1677, 1736, and 1771.

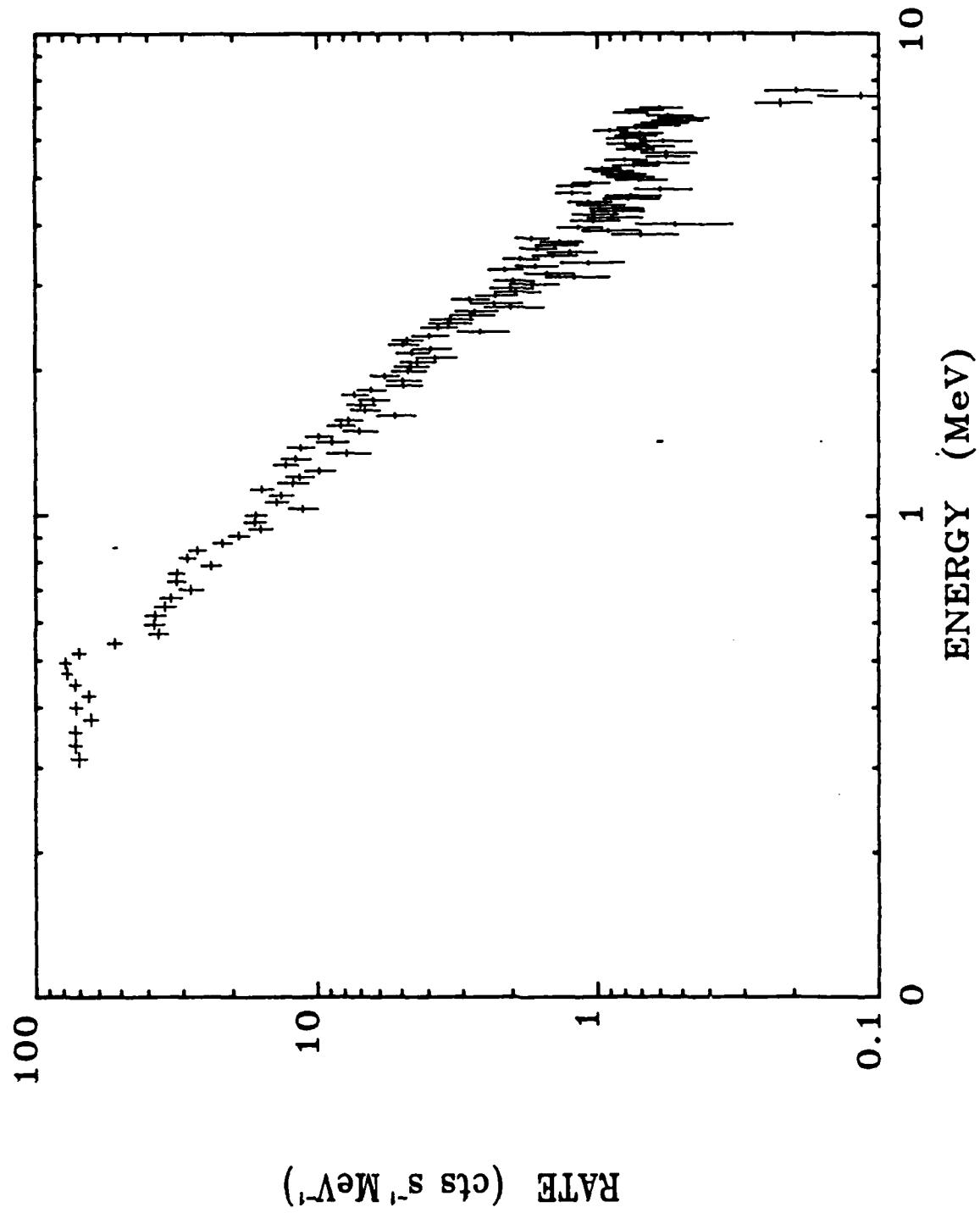


Fig. 3 - Integrated count-rate spectrum for close-approach sightings of the eleven RORSATS in operation from 1980 to 1986. Total accumulation time is 2519 s.

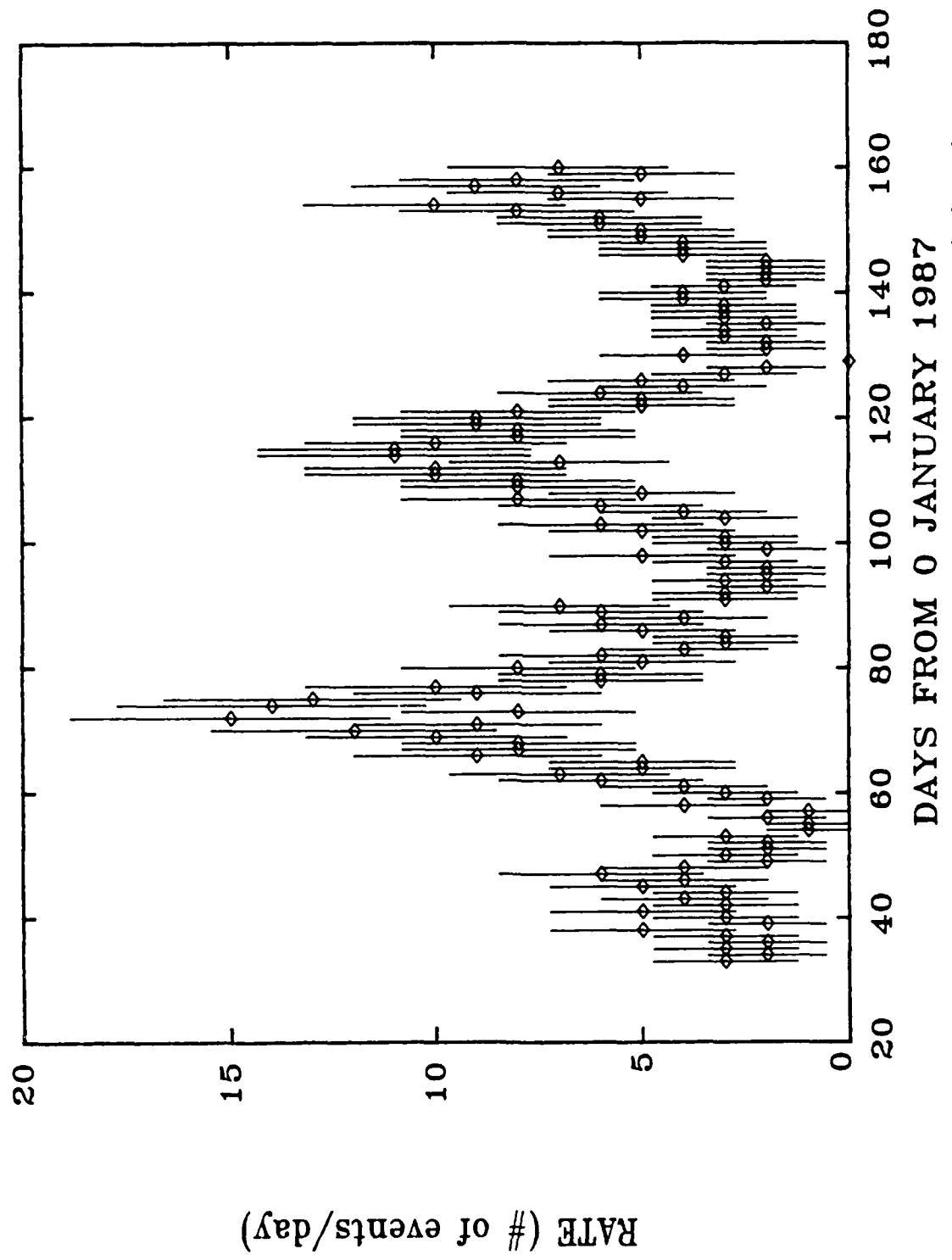
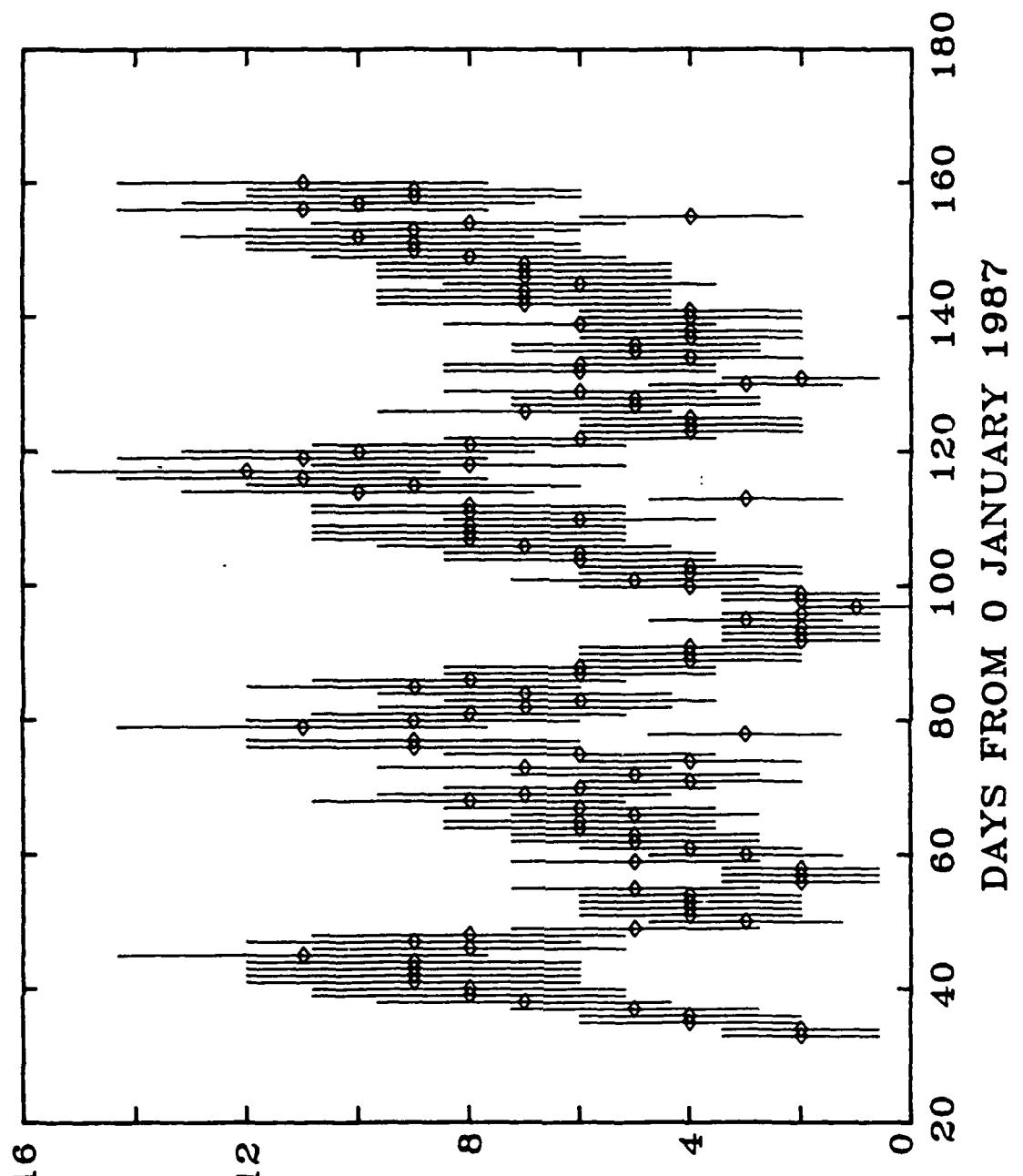


Fig. 4 - Rate of detection of bursts of annihilation radiation (positrons) found in a computer search of the SMM data from February to June 1987. The events commenced just after launch of COSMOS 1818.



RATE (# of events/day)

Fig. 5 - Rate of detection of transient electron events detected by the SMM spectrometer from February to June 1987. The events commenced just after the launch of COSMOS 1818.

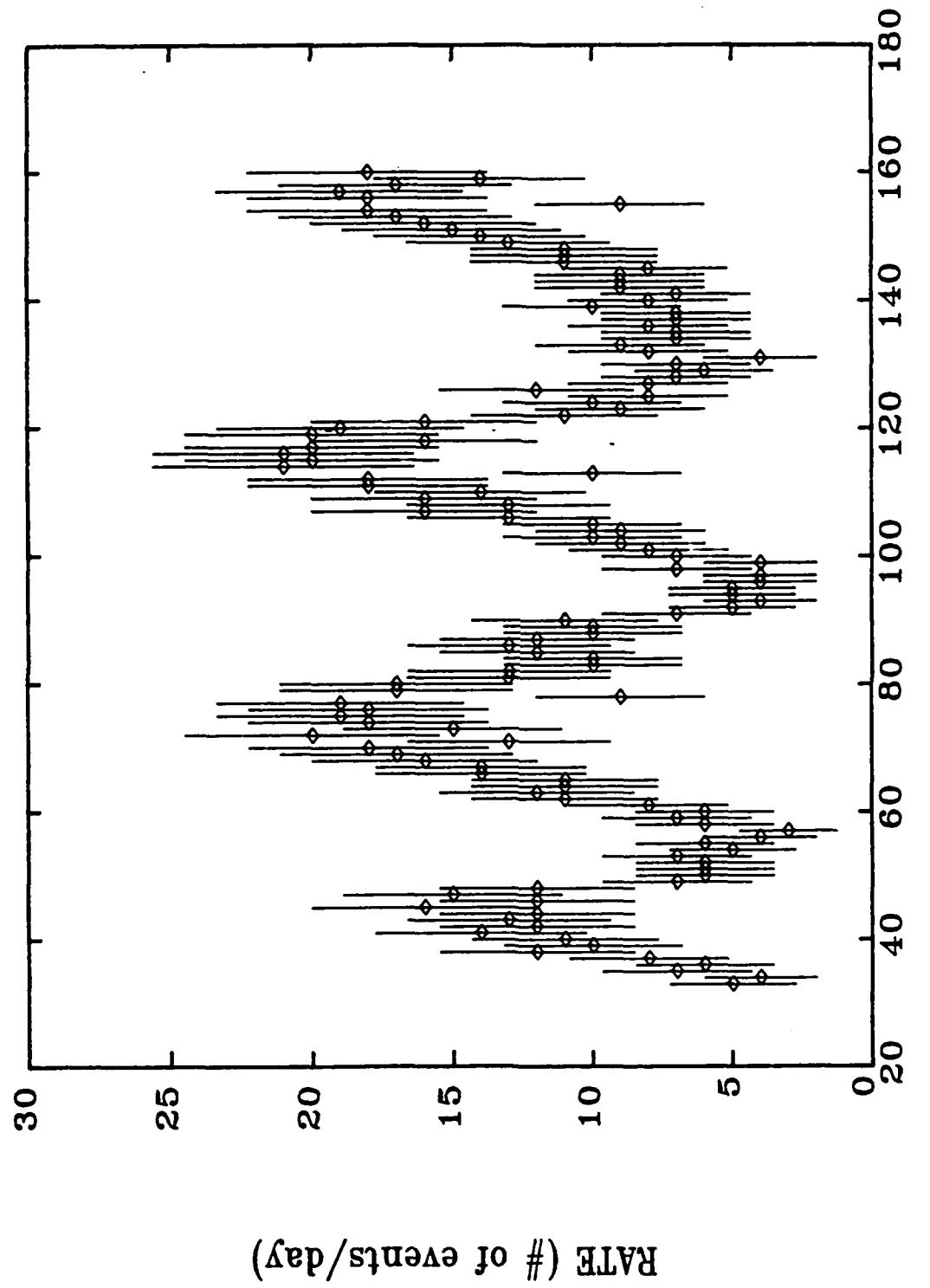


Fig. 6 - Rate of detection of the sum of transient positron and electron events by the SMM spectrometer from February to June 1987.

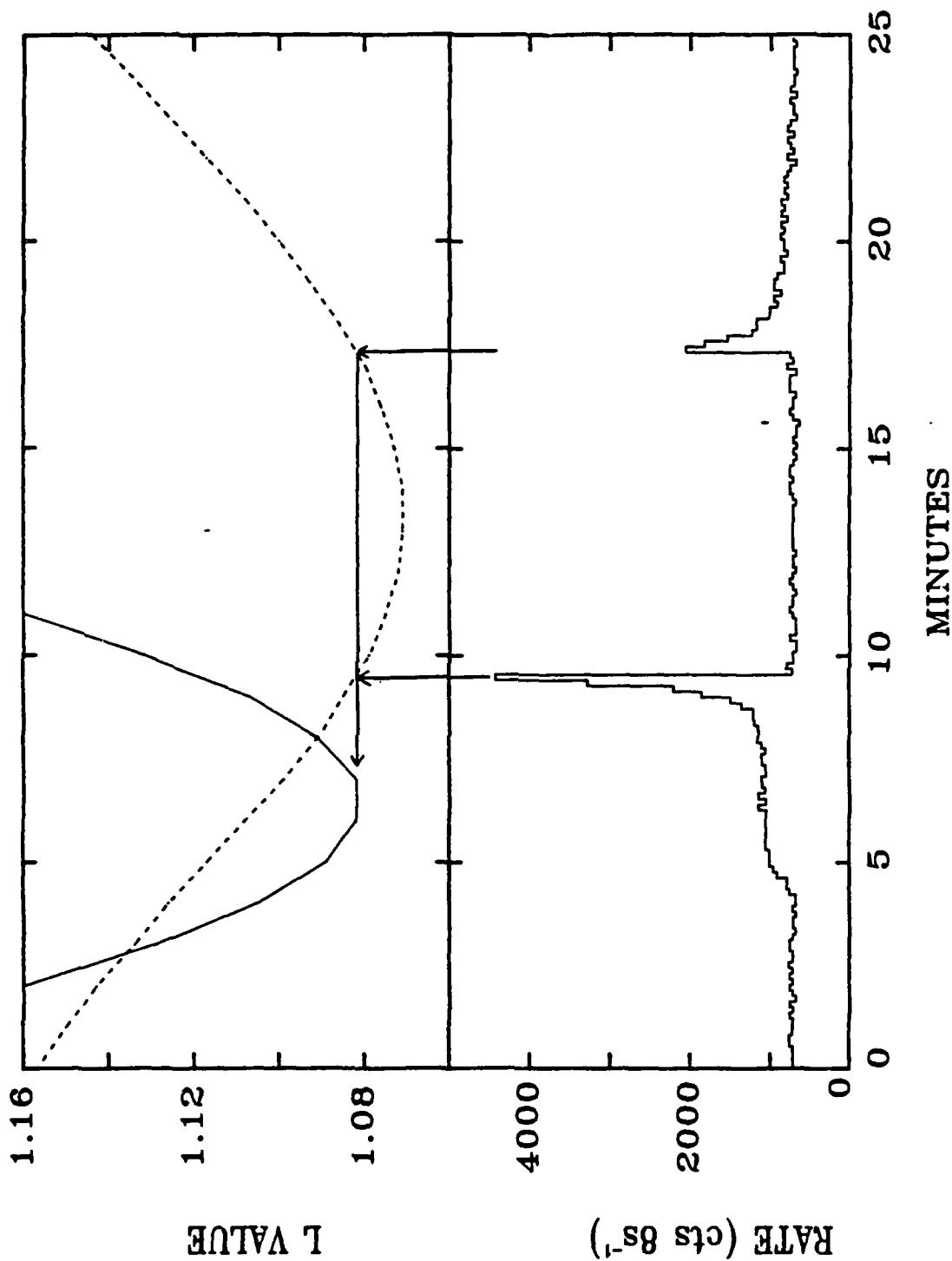


Fig. 7 -  
 a) Comparison of the variation of the McIlwain 'L' parameters for SMM, dashed curve, and COSMOS 1818, solid curve, during a period in which two extended electron transients were detected. b) The charged-particle rate observed during the same time period in plastic scintillation counters surrounding the SMM gamma-ray spectrometer.

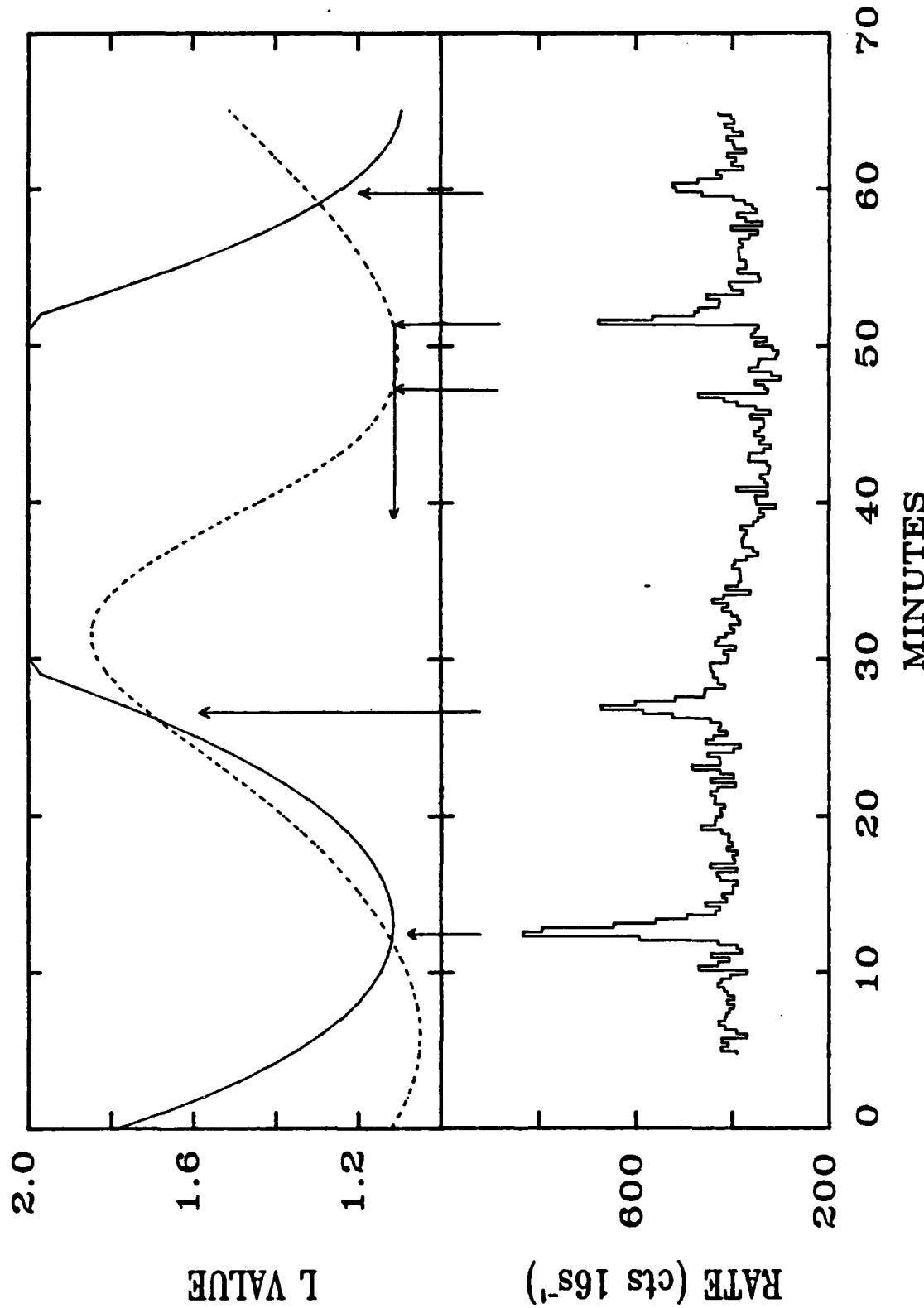


Fig. 8 - a) Comparison of the variation of the McIlwain L parameters for SMM, dashed curve, and COSMOS 1818, solid curve, during a period in which at least five positron transients were detected. b) The intensity of 511 kev annihilation gamma-rays detected during the same time period by the SMM gamma-ray spectrometer.

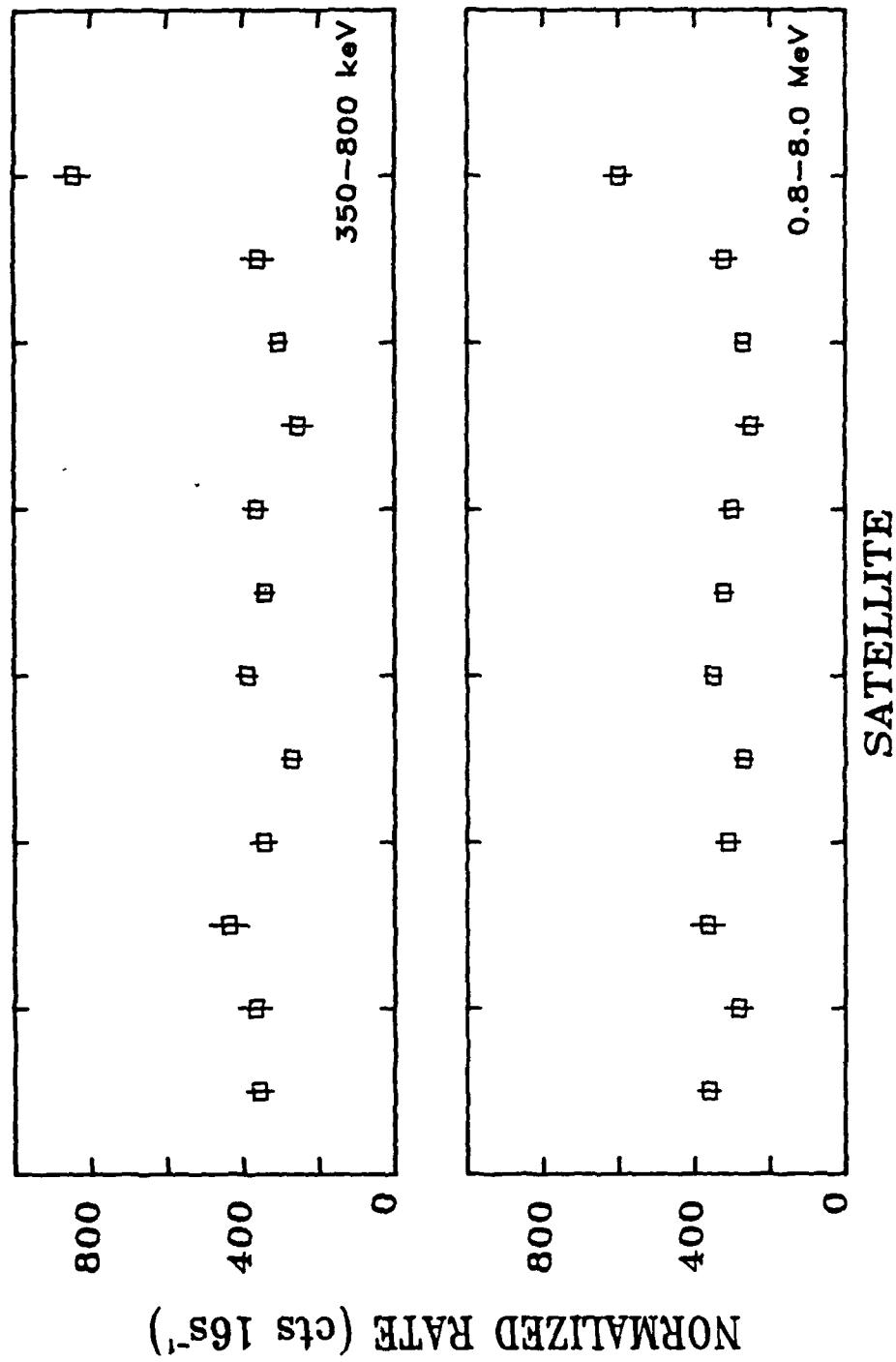


Fig. 9 - Average 0.35 to 0.8 MeV (a) and 0.8 to 8.0 MeV (b) counting rates in the SMM spectrometer, normalized to 300 km, during close-approach sightings of the eleven RORSATS observed prior to 1987 and COSMOS 1818. The COSMOS identification numbers from left to right are: 1176, 1249, 1365, 1372, 1402, 1579, 1607, 1677, 1736, 1771, and 1818.

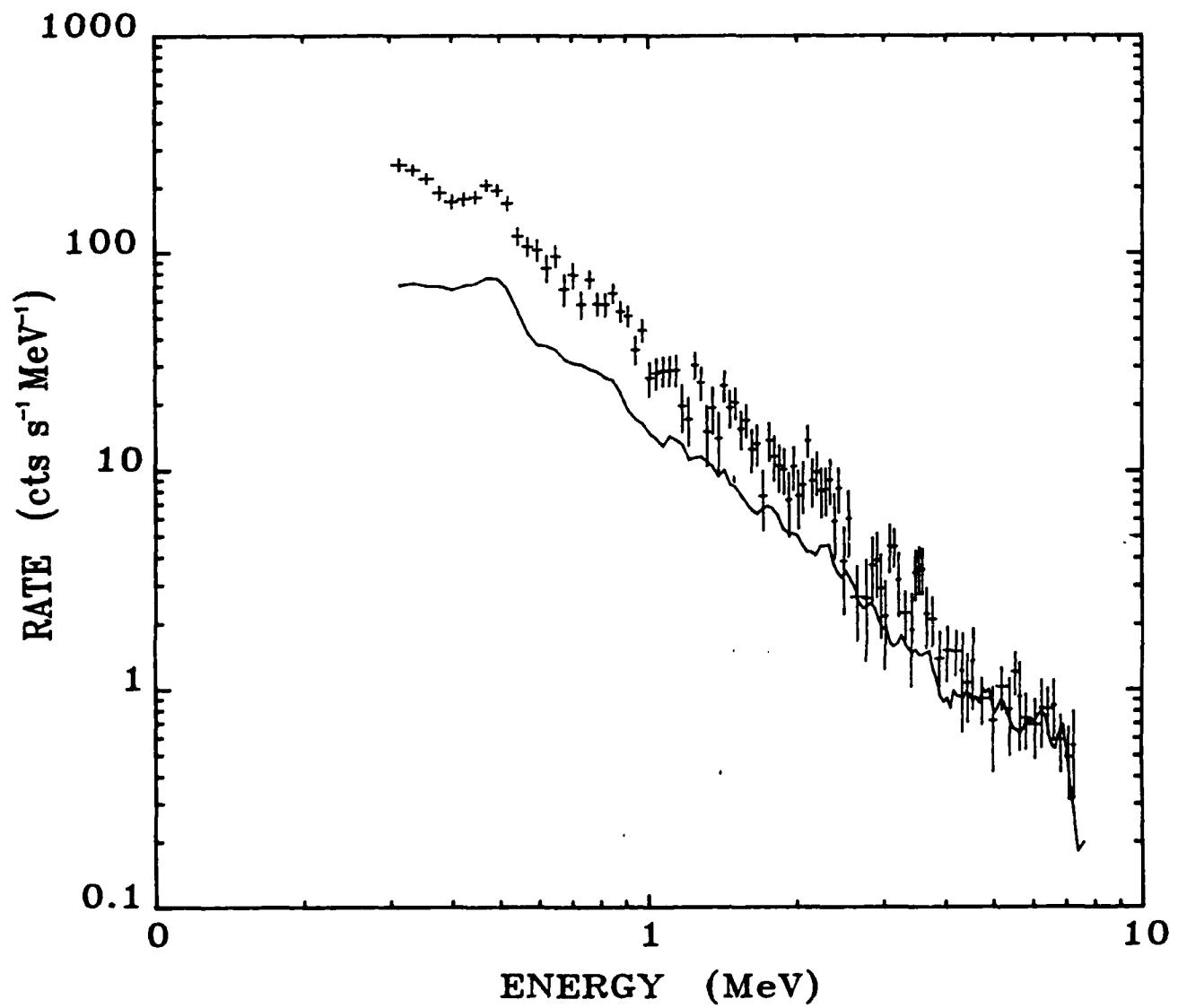


Fig. 10 - Integrated count-rate spectrum for close-approach sightings of COSMOS 1818. Total accumulation time is 522 s. Curve is smoothed representation of the integrated spectrum observed from RORSATS detected from 1980 to 1986 (Fig. 3). Both spectra have been normalized to detection at a distance of 300 km.

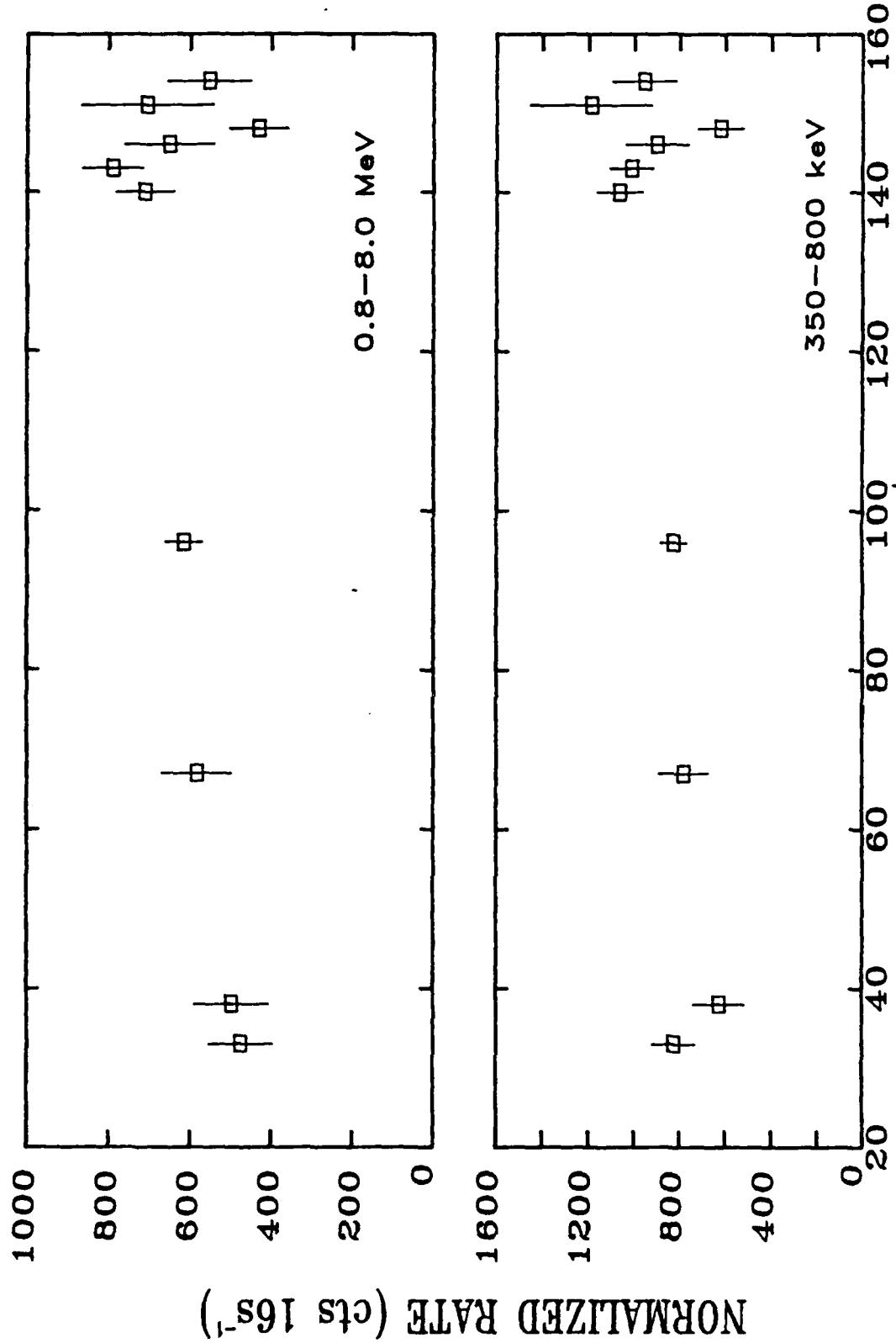


Fig. 11 - Intensities observed in the a) 0.35 to 0.8 MeV and b) 0.8 to 8.0 MeV energy ranges, normalized to detection at a distance of 300 km, in ten individual observations of COSMOS 1818 by SMM.